Fundamentals of a Motor Thermal Model and its Applications in Motor Protection

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1. Abstract

This paper discusses the fundamentals of a motor thermal model and its mathematical interpretation and physics for the different stages of motor operation. (overload, locked rotor, too frequent or prolonged acceleration, duty cycling applications). It explains Thermal Model Time Constants and other technical parameters that cause the biasing of the thermal model algorithm. Other topics covered in this paper show that (a) detailed motor data sheet information, and (b) coordination between the protection engineer and the motor supplier, can lead to proper selection of motor thermal protection parameters. This paper presents a closer look at motor stall, acceleration and running thermal limit curves. It also explains the concept of thermal capacity and elaborates on how thermal capacity is evaluated in motor protection devices. The following points are also covered in this paper:

- Discusses some additional methods, such as voltage-dependant and slip-dependant motor overload curves, employed to evaluate thermal capacity in nonstandard motor applications,

- Presents the concept of matching thermal time constants for motor cyclic loads cases. In addition, the response of a thermal model algorithm in practical applications is demonstrated.

- Describes a real case example showing how to apply and fine-tune the thermal model in high-inertia load application.

- Explores in this context, some of the key topics that will ensure safe operation of the motor while promoting satisfactory motor design characteristics.

2. Introduction

Induction motors are the workhorses of any industrial plant. Typical motor applications include pumps, fans, compressors, mills, shredders, extruders, de-barkers, refiners, cranes, conveyors, chillers, crushers, and blowers. Statistics have shown that despite their reliability and simplicity of construction, annual motor failure rate is conservatively estimated at 3-5% per year, and in extreme cases, up to 12%, as in the Pulp and Paper industry. Downtime in a factory can be very expensive and, in some instances, may exceed the cost of motor replacement. Proper machine protection is required to minimize the motor failure rate, prevent damage to associated equipment and to ensure both personnel safety and production targets.

The document "Report of Large Motor Reliability Survey of Industrial and Commercial Installations", published by the IEEE Motor Reliability Working Group [3] contains the results of IEEE and EPRI surveys on motor reliability and major causes of motor failure. The summary of these results is shown in Table I.

In spite of different approaches and criteria (IEEE failure groups are formed according to "cause of failure" and EPRI according to "failed component") both studies indicate a very similar failure percentage associated with mechanical- and electrical-related machine problems.

Analyzing the data from this table we can conclude that many failures are directly or indirectly related to, or caused

IEEE Study		EPRI Study		Average
Failure Contributor	%	Failed Component	%	%
Persistent Overload	4.2%	Stator Ground Insulation	23.00	Electrical Related Failures
Normal Deterioration	26.40%	Turn Insulation	4.00	
		Bracing	3.00	
		Core	1.00	
		Cage	5.00	33%
Electrical Related Total	30.60%	Electrical Related Total	36.00%	
High Vibration	15.50%	Sleeve Bearings	16.00	Mechanical Related Failures
Poor Lubrication	15.20%	Antifriction Bearings	8.00	
		Trust Bearings	5.00	
		Rotar Shaft	2.00	
		Rotor Core	1.00	31%
Mechanical Related Total	30.70%	Mechanical Related Total	32.00%	
High Ambient Temp.	3	Bearing Seals	6.00	Environmental Maintenance & Other Reasons Related Failures
Abnormal Moisture	5.8	Oil Leakege	3.00	
Abnormal Voltage	1.5	Frame	1.00	
Abnormal Frequency	0.6	Wedges	1.00	
Abrasive Chemicals	4.2			
Poor Ventilation Cooling	3.9			
Other Reasons	19.7	Other Components	21.00	
Environmental Reasons & Other Reasons Total	38.70%	Maintenance Related & Other Parts Total	32.00%	35%

Table 1.
Summary of IEEE and EPRI Motor Reliability Surveys.

by, extensive heating of the different motor parts involved in machine operation. That is why we find accurate tracking of motor thermal status and adequate response of the motor control system to abnormal situations to be very important.

Modern trends in motor design and construction are moving in the direction of making motors more compact and efficient. The use of inorganic insulation materials such as fiberglass and silicon resins provides improved dielectric motor insulation properties compared to legacy materials such as cotton and varnish. But at the same time some new materials are more vulnerable to excessive heating. Another important consideration that should be consdered in tracking the thermal state of the motor, is heating overestimation, which can also cause undesirable motor stoppage and hence potentially costly interruption of processes. The statements above clearly explain the importance of an accurate thermal estimate of a motor in service.

Currently this task (precise motor thermal protection) is strongly supported by modern technology. The developed algorithms can be implemented in microprocessor devices, which are capable of providing a desirable level of accuracy and flexibility.

The thermal algorithm operates as per the following sequence:

- Real-time motor data is supplied to microprocessor device.

- This data is processed according to the firmware thermal algorithm program and compared with expected values, stored in memory.

- The protection device computes the analog value, which is compared with the programmed threshold.

- The protection device triggers the digital outputs if the compared analog value exceeds this threshold.

The ideal analog method for modeling the thermal image in the Motor Protection Device (MPD) would be to embed non-inertial temperature sensors into the stationary (stator) and rotating (rotor) parts of the motor structure. However, it is not feasible to install temperature sensors in the rotors for technical reasons, reliability and cost. An additional reason to reject such temperature sensors as the main basis for thermal protection, is the fact that the traditional Resistance Temperature Detector (RTD) has a relatively slow reaction time and can't respond adequately to the high speed of the heating process during motor acceleration.

Stator RTDs actually provide realistic results in monitoring the temperature under balanced motor conditions, but again they are not suitable for monitoring the fast thermal transients.

Alternatively, a main real-time input thermal model could use 3-phase motor current. The electrical energy applied to the motor is partially transformed into heat which is stored in the motor. Thus this heat is a function of current and time. This fact, plus some other factors and assumptions that will be covered further in this paper, are employed to develop and implement the current-based thermal model. 3-phase current values measured in real-time are also used in special algorithms applied to detect different stages of motor operation: stopped, start, run, overload.

In high-inertia load applications voltage monitoring can be used in the thermal model algorithm to dynamically match the thermal limit to different starting conditions. In some applications speed sensors are employed to detect slow rotor rotation or motor stall.

Another important part of thermal model implementation is "Expected values stored in MPD". This term implies that information is available from the motor designer and motor manufacturer, that is related to the thermal reserve, allowed performance and thermodynamics of the motor in question.

The motor is not a homogeneous body and even one component can be presented as a combination of nodes connected via thermal resistance to each other and external ambient conditions. For example, the stator has slot copper, end-head copper, teeth and a core. Each node is characterized by its own rate of temperature change. [6]

That is why in order to do the full analysis and detect a boundary for normal operation, motor designers always target the development of the most detailed model including electrical, mechanical, thermal, and chemical components. But once a motor is properly designed and constructed to its intended specifications, a less detailed model is adequate to provide thermal protection by evaluating thermal risk with reference to motor data sheets and thermal damage curves.

Common sense dictates reliance on a complete motor analyses to determine the correspondence of the MPD algorithm variables to the data typically available from the motor manufacturer. MPD also incorporates simplified algorithms modeling physical motor states and processes. This approach allows us to attain an adequate level of thermal protection in modern MPD, for any application, by handling the available motor information. In trying to keep the algorithm simple we face another challenge. It is rather difficult to relate the thermodynamic behavior of the motor under steady-state conditions, with the rapid stator and rotor heating that occurs during thermal motor transients such as acceleration, stall and cyclic load change. The algorithm must also account for heat transfer from the motor's winding to the housing and from the housing to the free (ambient) air. To resolve this issue the "time before trip" parameter was selected as the common criterion for thermal condition evaluation. Actually, for motor acceleration and stall conditions, the safe stall time specified by motor designers, is the only objective estimate of the maximum allowable motor temperature, because of the real difficulty of directly measuring the rotor temperature. [6]

Based on the discussion in this section of the paper, the main motor thermal algorithm requirements can be summarized as follows:

- **Accuracy.** A precise estimate of the thermal motor image. Consideration of different motor applications, such as variable frequency, voltage unbalance, long acceleration, cyclic loads. Reference to data specified by motor designers.

- **Simplicity.** The algorithm is easy to understand. A simple way to calculate the thermal estimate of the motor for the operational sequence in question.

- **Dependability.** The capability of monitoring the thermal

capacity at any moment of motor operation. The thermal estimate is maintained and responds adequately to MPD power failure events.

- **Compliance to industry standards.** The algorithm must meet the requirements, and should follow the recommendations listed in, IEEE Guide for AC Motor Protection (Std C37.96-2000) [9] and IEEE Guide For the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines (Std 620-1996) [10].

- **Easy Setup.** The parameters required to set up the thermal model are obtained from the standard set of motor data readily available from motor manufacturers.

- **Reliability.** The model is supported by alternative motor temperature evaluation methods, based on RTD's monitoring. This backup method is extremely useful in cases where the thermal process significantly deviates from what was expected because of abnormal ambient temperatures or motor cooling impairment.

- **Flexibility.** The possibility of apply the model even in very unusual cases.

In addition to the accurate thermal model the state of the art Motor Protection Device should be equipped with the enhancements and additional functionality listed below.

- RTD Inputs for absolute temperature monitoring, alarming and tripping of the motor at high temperatures.

- Temperature-based stator thermal estimate, capable to correct main thermal model in the abnormal operational conditions

- A temperature-based stator thermal estimate, capable of correcting the main thermal model under abnormal operating conditions

- Wide selection of thermal overload curves; standard for typical applications, user defined for unusual applications and voltage dependant for special applications, featured long starts of high inertia loads.

- A Motor Start Lockout feature inhibiting the start of the machine in the case of non-availability of sufficient thermal reserve to complete the acceleration. The lockout time is calculated based on the available thermal capacity, the maximum learned value of Thermal Capacity Used (TCU) during one of the last 5 successful starts and the rate of temperature change for the motor at standstill.

- A wide selection of thermal overload curves; standard for typical applications, user-defined for unusual applications and voltage-dependant for special applications, featuring long starts of high inertia loads.

- Thermal model biasing in response to the current unbalance that causes an extensive heating effect.

- The option to select separate cooling constants for the motor in the stopped and running states.

- A current unbalance element capable of issuing a warning about a potentially dangerous level of unbalance and of tripping the motor off line on single–phasing.

- A Start Supervision Element preventing an excessive number of motor starting sequences.

- A mechanical Jam Detector.

- An acceleration limit timer.

- Phase Short Circuit and Ground Fault Protection Functions.

- Voltage and Frequency elements ensuring motor operation within specified limits. Phase Reversal Detection.

- Power Elements to monitor and respond to abnormal motor loading conditions.

- MPD failure detection.

- Communication capability to host computers to allow easy integration into existing DCS and SCADA systems.

- Cost justifiable.

- Can be adapted (retrofitted) to multi-vendor MCC's and motor starters.

- Industrially hardened by means of a conforming coating, to work in mill environment.

- Highly accurate predictions of mechanical and insulation failure, as well as the broken rotor bar condition, without removing the motor from service and without the need for resident experts.

- The capability of reading/capturing motor currents and voltages during electrical system faults.

- The capability of recording and storing in the device's nonvolatile memory, time-stamped events related to abnormal motor situations.

Additional protection functions can be provided using expensive equipment such as vibration sensors and/or instruments to display the current spectrum of the motor, to predict incipient failures. These are not covered in this document.

3. Thermal Protection Theory

There are two main types of thermal risks for an overheated motor: stator insulation may degrade and/or rotor conductors may decrease their capability to resist bending (deformation) forces or even melt. Deterioration of stator insulation presents the chemical process that is governed by an Arrhenius equation [6[, [7]. NEMA Motor Insulation Class defines the maximum allowable temperature rise above the
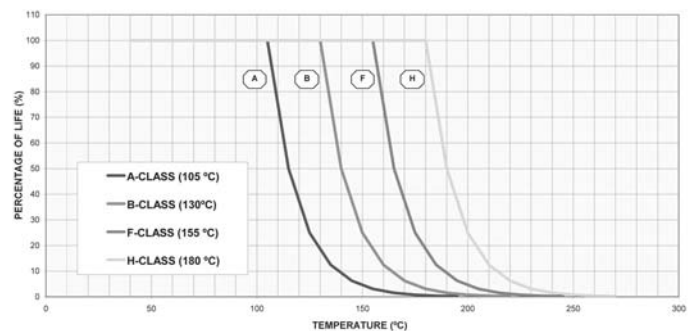

Fig 1.
Aging Factor of Motor Insulation.

ambient or thermal limit, if temperature exceeds this limit it doesn't cause immediate insulation failure but decreases the insulation's expected lifetime. A fairly accurate approximation of Arrhenius equation states that an operating temperature increase of 10°C in excess of the thermal limit cuts the life of stator insulation by half. The percent of life vs temperature characteristics for different classes of insulation are shown at Figure 1.

The thermal risk for a squirrel cage rotor is that the rotor conductors may deform or melt. Since there is no insulation, the rotor conductors can be operated at a much higher temperature than the stator conductors. It is difficult and impractical to provide a numerical temperature value defining the rotor thermal limit. Motor designers address the maximum allowable rotor temperature under stall, acceleration or any other fast transient conditions by stating the stall time thermal limits for a hot or cold motor. These values must correspond to the system voltage level during the stall event. For the majority of applications, the safe stall time defines the rotor thermal limit, but in some special cases motor capability during stall and acceleration is dictated by the stator thermal limit. A rule of thumb to define a stator-limited motor says: "When the voltage rating of the motor is equal to or greater than 10 times the horsepower rating, the motor is stator limited." For example: 500 HP, 6900 V. [8]

Steady-state operations such as running overloads are usually not an issue for the rotor. Under running conditions the stator is subject to extensive heating. Thus a stator overload protection element ensures an overall sufficient level of thermal protection for a rotor rotating at near synchronous speed.

The steady state and transient thermal behavior of the stator and rotor conductors of a motor depends on the details of the motor thermal circuit. The motor designer typically uses a rather detailed thermal circuit, including separate representations of stator iron, rotor iron, stator conductors, rotor conductors, internal air, external air, motor shell and end shields. Details of the thermal circuit depend on the ventilation construction of the motor, including "drip proof", "totally enclosed fan cooled", and "totally enclosed non-ventilated". For example, heat storage in each circuit element as well as convective or conductive heat transfer between various pairs of circuit elements is included in the model. A typical motor thermal circuit used by a motor designer may have on the order of 20 nodes and 20 branches, resulting in a dynamic response characterized by several time constants.

Motor designers are typically interested in a few standard thermal scenarios including steady state loading, cold, hot and successive starting. The designer checks the computed steady-state temperature of the stator winding to make sure it is within the capability of the selected insulation system, designers also define the time limits to withstand overloads. It is also very important to determine running and stopped motor cooling rates especially for "totally enclosed non-ventilated" motor designs and in some applications with intermittent use ratings. The motor designer is also interested in allowable cold and hot

stalled times. Stalled thermal calculations are usually performed assuming adiabatic conditions. The designer often concedes the fact that the peak temperature of the stator winding may temporarily exceed the steady state capability of the insulation system, taking into account the expected application of the motor and how many times it is expected to be stalled cold or hot in a lifetime, in making a design compromise. After a design is complete, a summary of the thermal model becomes available. Basic information includes the steady state thermal rating of the motor, hot and cold stall times, and the cooling time constants of the motor. For medium and large motor designs complete thermal damage curves of allowable time versus current are provided as a standard.

Once the motor has been designed, and the basic operational parameters have been established for steady state load and cold and hot stall times, the responsibility shifts to thermal protection for the motor. For majority of service conditions the operating profile of the motor matches the assumptions made by the motor designer, so that the main job of thermal protection is to stay out of the way and let the motor run. However, if motor is abused by mechanical breakage or human error then protection steps in to assure there is no risk of thermal damage.

The question is, what model should be used to protect the motor when it is running? What is a reasonable compromise between accuracy and complexity? What physics should be included? What should be used as an estimate of operation limit?

As we mentioned before the ideal method would be to have the direct accurate temperature measurement and use aging factor to estimate the consumed motor thermal capacity. But temperature sensors (RTD) have a delayed response to thermal transients such as stall and acceleration and can't serve as a basic criterion for a thermal model.

How detailed should the model be?

We should certainly provide a model with enough flexibility to protect motors that have a dynamic thermal response represented by several time-constants. A single time-constant is not always adequate [6]. Physics shows that there are at least 4 distinct thermal time-constants: 2 for the stator conductors, and 2 for the rotor conductors. For example, when heat is generated in the stator conductors, the first effect is to raise the temperature of the conductors. The stator winding in the stator slots are surrounded by a steel magnetic core. Therefore, as the windings get hot, heat begins to flow from the windings into the steel core. The combination of the thermal capacity of the winding and the thermal conductivity/impedance between the winding and the steel core establishes a short time-constant. Heat that continues to flow from the winding into the surrounding core is stored in the core, causing its temperature to rise, but more gradually than the initial rate of rise of the windings, because of the greater thermal capacity of the core. Eventually, the temperature of the core (and the motor frame, etc.) also rises, causing heat transfer by convection to the surrounding air. The combination of the thermal capacity of the core and the frame and the thermal impedance between them and the cooling air establishes a time-constant that is much

longer than that of the winding-core interaction.

So, the next question is, what is the best way to go beyond a single time-constant model?

The most reasonable way to model the thermal state of the motor is to measure motor current and to correlate it in real time to motor thermal damage curves. The manufacturer's thermal damage curves represent the results of simulations of a complete motor model, including a multi-node thermal model. The curves capture the multi-time-constant parameters and thermal damage times for running, stall and sometimes acceleration conditions of the motor. Typical curves are shown at Figure 3. Any point on the motor thermal damage curve represents a thermal time limit at a specific level of current, or in other words: "The thermal limit defines how long a motor can withstand the corresponding level of stator current without exceeding the thermal boundary specified by the motor manufacturer." Details of the thermal model implementation, based on overload curves are given in the next section.

In this section we answer two important theoretical questions concerning a thermal model based on motor thermal damage curves (overload curves):

1. What is the relationship between standard overload curves and a single time-constant thermal model?

2. Does an overload curve based thermal model behave correctly when it is used in applications in which the load is not constant?

We turn to mathematical analyses of the physics to answer theses two questions, starting with an analysis of a single time-constant model. The thermodynamic behavior of homogeneous body at rest (motor) heated by electrical current can be described by a single time-constant thermal equation:

$$C \cdot \frac{dT'(t)}{dt} = I'^2(t) \cdot R - H \cdot T'(t)$$

$T'(t) = $ motor temperature rise above ambient

$I'(t) = $ motor current

$C = $ specific heat capacity of the motor

$H = $ running heat dissipation factor

$R = $ electrical resistance

(1)

It is convenient to rewrite equation (1) in terms of per unit temperature rise and per unit current:

$$T(t) = T'(t)/T_{max} = \text{per unit temperature rise}$$
$$I(t) = I'(t)/I_{rated} = \text{per unit current}$$
$$I_{rated} = \text{rated current}$$
$$T_{max} = \text{motor temperature at thermal limit trip condition}$$

(2)

In that case, equation (1) can be rewritten as:

$$\tau \cdot \frac{dT(t)}{dt} = I^2(t) \cdot \frac{I_{rated}^2 \cdot R}{H \cdot T_{max}} - T(t)$$

$$\tau = \frac{C}{H}$$

(3)

The maximum temperature is related to the rated current such that $\frac{I_{rated}^2 \cdot R}{H \cdot T_{max}} = 1$. In that case, equation (3) can be rewritten as:

$$\tau \cdot \frac{dT(t)}{dt} = I^2(t) - T(t)$$

(4)

Equation (4) can be used to analyze the thermal response of a single time-constant model to a steady overload. It can be shown that the solution of equation (4) for a steady overload, starting from a cold initial condition, is given by:

$$T(t) = I^2 \cdot \left(1 - e^{-t/\tau}\right)$$

$I = $ per unit motor current (a constant)

$T(t) = $ per unit motor temperature rise

(5)

Equation (5) can be solved for the amount of time needed for the temperature rise to reach the thermal limit of the motor, i.e. T(t)=1:

$$t_{max}(I) = \tau \cdot \ln\left(\frac{I^2}{I^2 - 1}\right)$$

$t_{max}(I) = $ time estimated by a simple thermal
model for the motor temperature to
reach thermal limit

(6)

To develop a comparison between a single time constant thermal model and overload curves, we now turn our attention to standard overload curves, which are given by:

$$t_{max}(I) = \frac{87.4 \cdot CM}{I^2 - 1}$$

$t_{max}(I) = $ trip time, seconds

$CM = $ curve multiplier

(7)

To compare standard overload curves with the behavior of a single time constant model, it is useful to start by recognizing that the numerator of the right hand side of equation (7) corresponds to a time constant:

$$t_{max}(I) = \frac{\tau_{CM}}{I^2 - 1}$$

$$\tau_{CM} = 87.4 \cdot CM$$

(8)

Equation (6) and equation (8) are plotted in Figure 2. In order to make the curves align for large values of current, it is necessary to satisfy the following constraint:

$$\tau = \frac{C}{H} = \tau_{CM} = 87.4 \cdot CM$$

(9)

In other words, in order for an overload curve to match a single time-constant thermal model during a simple step overload, the
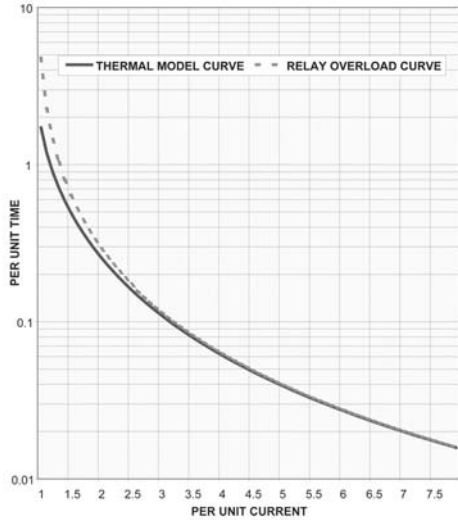
Fig 2.
Single Constant Thermal Model vs Relay Overload Curve Comparison

time-constant implied by the curve multiplier of the overload curve must be set equal to the time-constant of the single time-constant model. In Figure 2, the ratio of the time divided by the time-constant is plotted against per unit current. It can be seen that although equation (6) is not exactly the same as equation (8), the approximation is very close, particularly for large values of current. For lower values of current, the standard overload curves are a better approximation to typical motor overload curves than a single time-constant model. That is because there are at least two time-constants in the thermal response of a motor. Over short time intervals, the thermal response of a motor is dominated by heat transfer from the stator and rotor conductors to iron. Over longer time intervals, the thermal response is dominated by heat transfer from the iron to cooling air. A single time-constant model cannot be accurate over the full range of operation and tends to overprotect a motor when it is operated near its rated load. A standard overload curve provides protection that is a closer match to a motor's thermal limit. The close proximity of the two curves for large values of current is not a coincidence because both models are equivalent to an adiabatic model for large values of current. This can be shown mathematically by finding the asymptotic behavior of the two curves. First, equation (8) is given approximately by:

$$t_{max}(I) = \frac{\tau_{CM}}{I^2 - 1}$$

$$t_{max}(I) \approx \frac{\tau_{CM}}{I^2} \qquad I^2 >> 1 \tag{10}$$

A similar approximation can be shown to hold for equation (6) by rewriting and taking a Taylor's expansion in terms of the reciprocal of the square of the current. First, we rewrite to explicitly show the dependence on the reciprocal of the square of the per unit current:

$$t_{max}(I) = \tau \cdot \ln\left(\frac{I^2}{I^2 - 1}\right)$$

$$t_{max}(I) = \tau \cdot \ln\left(\frac{1}{1 - 1/I^2}\right) = -\tau \cdot \ln\left(1 - 1/I^2\right) \tag{11}$$

$$t_{max}(I) = -\tau \cdot \ln(1 - x)$$

$$x = 1/I^2$$

We then take the first two terms in a Taylor's expansion of $h(1-x)$ with respect to x around the point $x = 0$:

$$\ln(1 - x) \approx \ln(1) - x \approx -x \qquad x << 1$$

$$\therefore t_{max}(I) \approx \frac{\tau}{I^2} \qquad I^2 >> 1 \tag{12}$$

Equation (8) describes how long it will take a standard overload curve to reach thermal limit for a constant overload. We now turn our attention to how a standard overload curve behaves during cycling loads. We start with the differential equation that is used to implement standard overload curves:

$$\frac{dT(t)}{dt} = \frac{I^2(t) - 1}{\tau_{CM}} \tag{13}$$

To gain insights into what the response is to a cycling load, we will consider a simple cycling load in which the current alternates between no load and an overload value:

$$I_{low} = 0 \approx \text{current during the low cycle}$$

$$I_{high} = \text{current during the high cycle}$$

$$t_{low} = \text{time interval for the low cycle} \tag{14}$$

$$t_{high} = \text{time interval for the high cycle}$$

Motor heating is proportional to the square of the current, so the effective current for heating over the cycle is:

$$H_{effective} = I_{effective}^2 = \frac{t_{high} \cdot I_{high}^2 + t_{low} \cdot I_{low}^2}{t_{low} + t_{high}}$$

$$I_{effective} = \text{effective value of the load current} \tag{15}$$

$$H_{effective} = \text{effective heating value of the load}$$

Equation (15) can also be expressed in terms of a duty cycle ratio:

$$H_{effective} = D \cdot I_{high}^2 + (1 - D) \cdot I_{low}^2$$

$$D = \text{duty cycle ratio} = \frac{t_{high}}{t_{low} + t_{high}} \tag{16}$$

If the current and heating are expressed in per unit and the low cycle current is approximately equal to zero, the steady state boundary condition for tripping the motor becomes:

$$1 = D \cdot I_{high}^2 \tag{17}$$

Equation (17) defines the appropriate response to a duty cycle. It can be shown that a single time-constant model provides approximately this response. The next question is what is the response of a standard overload curve to a duty cycle? Analysis of a standard curve under load cycling conditions will show that the response is correct, and will reveal how to properly set an overload curve model to match the behavior specified by equation (17). We must consider values of current below pickup, during which our motor thermal model is defined by the following differential equation:

Motor Thermal Model Protection Applications

$$\frac{dT(t)}{dt} = \frac{1}{\tau_{cool}} \cdot \left(I \cdot \left(1 - \frac{hot}{cold}\right) - T(t) \right) \tag{18}$$

τ_{cool} = cooling time constant

hot = hot stall time

$cold$ = cold stall time

The factor $\left(1 - \dfrac{hot}{cold}\right)$ is included to match the hot and cold stall times specified by the motor manufacturer. By including the factor in the cooling computation, the hot overload curve is effectively shifted down by the correct amount relative to the cold overload curve to account for the difference in "time to trip" of hot and cold motor conditions.

For the load cycle under consideration, the current during the unloaded part of the cycle is approximately equal to zero, so the differential equation given by (18) reduces to:

$$\frac{dT(t)}{dt} = -\frac{T(t)}{\tau_{cool}} \tag{19}$$

Taken together, equations (19) and (13) describe the behavior of our model during the assumed load cycle. The approximate temperature rise during the overload portion of the load cycle estimated by the overload curve is computed by multiplying equation (13) by the overload time:

$$\Delta T_{high} \approx \frac{1}{\tau_{CM}} \cdot \left(I_{high}^2 - 1 \right) \cdot t_{high} \tag{20}$$

The approximate temperature drop estimated by the cooling model during the unloaded portion of the duty cycle is computed by multiplying equation (19) by the appropriate time, with per unit temperature equal to 1, because that is what it will be approximately equal to during a limit cycle that approaches tripping:

$$\Delta T_{low} \approx -\frac{1}{\tau_{cool}} \cdot t_{low} \tag{21}$$

The overload detection boundary is determined by setting the net temperature change equal to zero. This implies that the total of the right hand sides of equations (20) and (21) taken together is equal to zero:

$$\Delta T_{high} + \Delta T_{low} = \frac{1}{\tau_{CM}} \cdot \left(I_{high}^2 - 1 \right) \cdot t_{high} - \frac{1}{\tau_{cool}} \cdot t_{low} = 0 \tag{22}$$

Equation (22) can be rearranged to show that standard overload curves respond correctly to cycling loads. Equation (22) also reveals how to properly select parameters for a load cycling applications:

$$1 = \frac{\tau_{cool}}{\tau_{CM}} \cdot D \cdot I_{high}^2 \tag{23}$$

Equation (23) expresses the actual overload detection boundary of an overload curve model in terms of its settings, the duty cycle, and the amount of overload. Except for the factor of $\frac{\tau_{cool}}{\tau_{CM}}$, equation (23) is exactly the same as the ideal overload detection boundary, specified by equation (17). Equation (23) and equation (17) will be identical, provided that $\frac{\tau_{cool}}{\tau_{CM}}$ is set

equal to one resulting in the following consistency constraint:

$$\tau_{cool}(\min) = \frac{87.4 \cdot CM}{60} \tag{24}$$

Equation (24) represents a consistency constraint relating the cooling time-constant and the curve multiplier of a standard overload curve. Figure 9 shows what can happen if it is not satisfied. There are three cases shown for a cycling load with an approximate per unit heating value of one. In the first case, the cooling time-constant is set too long resulting in over-protection and early motor tripping. In the second case, the cooling time-constant is set according to equation (24) to match the implied time-constant of the curve multiplier, and the protection is correct. In the third case, the cooling time-constant is set too short, resulting in under-protection and possible motor overheating.

4. Thermal Model Algorithm

The thermal model algorithm was developed in order to create the thermal image of the motor and closely track the thermal conditions for all states of motor operation. The following states of motor operation are recognized:

- **Motor Stopped:** Current is below zero level threshold and motor switching device indicates the open status.

- **Motor Starting:** State is declared when previous state was "Stopped" and current greater than 2% of the motor full load amps has been detected. The motor current must increase to the level of overload pickup (service factor times full load amps) within 1 second otherwise motor will transfer into the next state: "Running"

- **Motor Running:** State is declared when previous state was "Starting" and motor current drops below overload pickup level.

- **Motor Overloaded:** State is declared when previous state was "Running" and motor current raises above the overload pickup level.
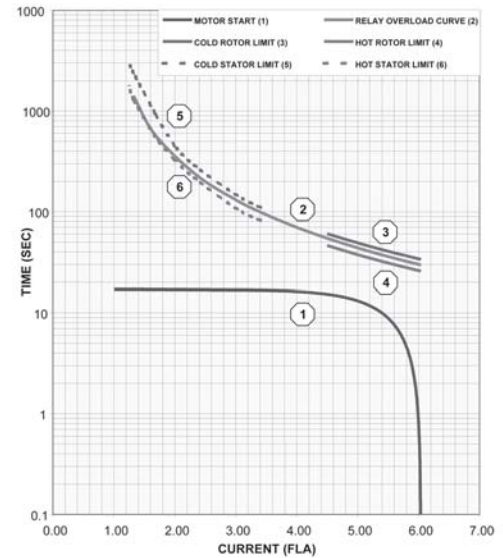

Fig 3.
Motor Thermal Limit Curves

Thermal Capacity Used (TCU) evaluates the thermal condition of the motor. TCU is expressed as percentage of the thermal limit used during motor operation. Per IEEE Std 620-1996 (10) the motor thermal limit is presented in the form of a time-current curve for 3 possible motor overload conditions: locked rotor, acceleration and running overload. Every point on this curve represents the maximum allowable save time at a stator current above normal load.

TCU is incrementally updated every 100 milliseconds and the integrated value of TCU is stored in the thermal memory register of MPD according to the following equation.

$$TCU_{@T} = TCU_{@T-1} + \frac{TIME\ INTERVAL}{TIME-TO-TRIP} \times 100\% \qquad (25)$$

The following example can be a good illustration of TCU accumulation during the cold motor start; initial TCU is equal to 0%. Motor starting pattern (1) and relay overload curve (2) are shown at Figure 3.

For simplicity assume that the time interval for TCU update is 1 second. Every point of motor current on this plot corresponds to the number of seconds that motor can withstand before tripping on overload. The numerical values showing the progress of TCU accumulation during 17 seconds of motor acceleration are presented in table 2. We can observe that by the end of a successful starting the thermal memory of the motor protection device (MPD) accumulates 46.7% of TCU.

ACCEL. TIME (SEC)	ACCEL. CURRENT	TIME-TO-TRIP	TCU@T-1	TCU@T
0	6.04	29.6	-	0
1	5.99	30.1	0.0	0% + (1sec/29.6sec) x 100% = **3.4%**
2	5.94	30.6	3.4	3.4% + (1sec/30.1sec) x 100% = **6.7%**
3	5.89	31.1	6.7	6.7% + (1sec/30.6sec) x 100% = **10.0%**
4	5.84	31.7	10.0	10.0% + (1sec/31.1sec) x 100% = **13.2%**
5	5.78	32.4	13.2	13.2% + (1sec/31.7sec) x 100% = **16.3%**
6	5.71	33.1	16.3	16.3% + (1sec/32.4sec) x 100% = **19.4%**
7	5.65	34.0	19.4	19.4% + (1sec/33.1sec) x 100% = **22.4%**
8	5.57	34.9	22.4	22.4% + (1sec/34.0sec) x 100% = **25.4%**
9	5.49	36.0	25.4	25.4% + (1sec/34.9sec) x 100% = **28.3%**
10	5.40	37.3	28.3	28.3% + (1sec/36.0sec) x 100% = **31.0%**
11	5.29	38.8	31.0	31.0% + (1sec/37.3sec) x 100% = **33.7%**
12	5.17	40.7	33.7	33.7% + (1sec/38.8sec) x 100% = **36.3%**
13	5.03	43.2	36.3	36.3% + (1sec/40.7sec) x 100% = **38.8%**
14	4.85	46.6	38.8	38.8% + (1sec/43.2sec) x 100% = **41.1%**
15	4.60	52.1	41.1	41.1% + (1sec/46.6sec) x 100% = **43.2%**
16	4.18	63.6	43.2	43.2% + (1sec/52.1sec) x 100% = **45.1%**
17	1.03	17221.7	45.1	45.1% + (1sec/63.6sec) x 100% = **46.7%**

Table 2.
Thermal Capacity Used (TCU) calculation.

Typically the motor manufacturer provides locked rotor thermal limit curves or locked rotor safe stall time values for 2 motor conditions: cold motor (motor @ ambient temperature) and hot motor (motor @ ambient + rated rise temperature). In order to distinguish between the 2 aforementioned motor conditions the additional motor parameter, Hot/Cold Stall Time Ratio (HCR) is included in MPD algorithm.

These parameters define the proportional increase of TCU of the motor running fully loaded at a settled temperature compared to the motor resting at ambient temperature. For example let us assume that according to the motor data sheets the Cold Safe Stall Time is 10 seconds and the Hot Safe Stall Time is 8 seconds.

Thus HCR is 8 sec / 10 sec = 0.8 and the level of stabilized TCU featuring the hot motor is equal to 20%, or in other words the allowed motor thermal withstand time at overload conditions will effectively decrease by 20%. If the motor load is lower then 100% the TCU level corresponding to the hot motor condition is proportionally lower: 75% load – 15% TCU, 50% load – 10% TCU and so on.

The unbalanced stator phase current will cause additional rotor heating due to the developed negative sequence current and flux rotating in the opposite direction to rotor rotation with approximately double the power system frequency. The skin effect in the rotor bars at this frequency will cause a substantial increase in rotor resistance and hence increased heating, which is not accounted for by the regular thermal model. In order to account for this additional heating factor the **Equivalent Current** concept is introduced. The idea is that the current input into the thermal model is biased to reflect the additional heating caused by the negative sequence component of the load current.

$$I_{EQ} = \sqrt{I_M^2 \times (1 + K \times (I_2/I_1)^2)} \qquad (26)$$

where:

I_{EQ} - equivalent motor heating current

I_M - real motor current

I_1 - positive sequence component of real motor current

I_2 - negative sequence component of real motor current

K - unbalance bias factor

The Unbalance Bias K factor reflects the degree of extra heating caused by the negative sequence component of the load current and can be defined as the ratio of Positive Sequence Rotor Resistance to Negative Sequence Rotor Resistance. It is practical and quite accurate to use the estimate method to define the K factor. Equations for typical and conservative estimates are presented below.

$$K = 175/I_{LRC}^2 \quad (typical) \qquad (27)$$
$$K = 230/I_{LRC}^2 \quad (conservative)$$

where I_{LRC} is the motor locked rotor current.

Of cause, in order to provide a complete thermal model of the motor in service, the cooling process must be taken into account. Cooling is characterized by Cooling Time-constants. These constants define the rate of cooling under stopped and running operating conditions.

When the motor is running at rated load, TCU accumulated during the motor start will decay exponentially and will stabilize at the level of TCU matching hot motor thermal conditions. If the motor load is lower, then obviously the thermal balance point is proportionally reduced.

The stopped motor will also be subjected to the exponential decay of TCU stored in MPD thermal memory during motor operation. Natural cooling of the rotating motor or forced cooling by means of the special fans installed on the machine shaft cause a much higher cooling rate of the running machine compared to the motor at standstill, typically the ratio is 2:1.

Thus 2 separate Cooling Time-Constants are used in the Thermal Model Algorithm. The equations to calculate TCU decay of the cooling motor are as follows:

$$_{TART} - TCU_{END}) \times e^{-t/\tau} + TCU_{END} \qquad (28)$$

Where:

$TCU_{START}(\%)$ is the initial value of TC accumulated by the moment the cooling starts;

$t\,(min)$ is duration of cooling;

$\tau\,(min)$ is the Cooling Time Constant;

$TCU_{END}(\%)$ is the steady state level of TC

The steady state thermal condition for the motor at stand still is the ambient temperature, which is corresponding to

$$TCU_{END}(\%) = 0. \qquad (29)$$

The steady state thermal condition for the running motor is calculated as:

$$TCU_{END} = \frac{I_{eq}}{SF \times FLA} \times (1 - HCR) \times 100\% \qquad (30)$$

Where:

I_{eq} is the value of the equivalent heating current accumulated by the moment cooling;

SF is the service factor of the motor;

FLA is the motor full load current (per unit);

HCR is the hot to cold safe stall time ratio

In some unforeseen situations, when the motor cooling is blocked or ambient temperature deviates significantly from the industry standard value (40ºC), it becomes difficult to accurately replicate the motor's thermal condition based solely on the measured current. That is why it is practical to apply an independent algorithm, calculating TCU by means of stator RTDs (resistance temperature detectors) and correcting the thermal model upwards if needed.

The RTD-TCU Curve is constructed based on the 3 key points. See Figure 4 for details.

1. RTD bias minimum

Set to 40°C or another value of ambient temperature, if the appropriate RTD is available. TCU is equal to 0%.

2. RTD bias mid point

The mid-point temperature is set according to the motor's hot running temperature and is calculated as follows:

Rated Temperature Rise + Ambient Temperature

For example: The temperature rise for NEMA Class B motors with 1.15 Service Factor, is 90ºC. Thus the temperature value for this point is 130ºC. The TCU quantity for this point is the value of a steady-state running condition @ rated motor load, and can be found as:

$$TCU_{CENTER} = (1 - HCR) \times 100\% \qquad (31)$$

3. RTD bias maximum

This point is set to the temperature rise equal to the motor insulation thermal limit.

Typically for NEMA B class motors insulation class is F with temperature rise above ambient of 115ºC. The TCU at maximum temperature point is equal to 100%.

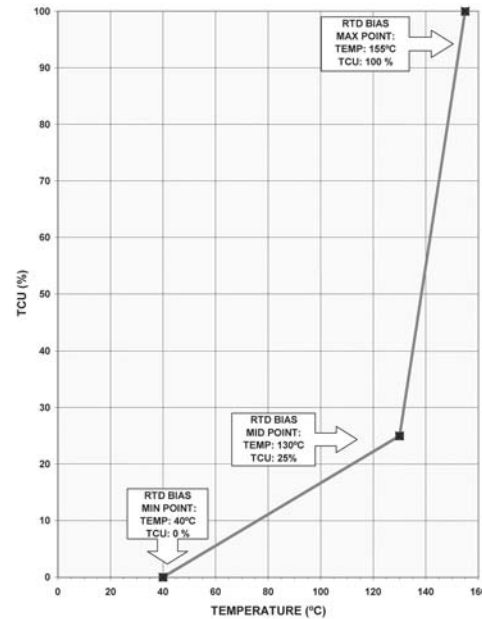Rate of change of TCU between the adjacent points is approximated as linear.

Fig 4.
RTD Bias of Thermal Model

5. Thermal Model Behavior at Different Operational Conditions

In order to illustrate how TCU varies during motor operation let us review the following motor data and operational sequences.

Let us assume that the following motor information is available to us.

- Motor thermal limit curves are as presented at Figure 3.

- Motor Cold and Hot Locked Rotor Times at 100% of the system voltage are 34 and 26 seconds respectively. At 80% of the system voltage Cold and Hot Locked Rotor Times are 50 and 38 seconds respectively.

- Motor Acceleration at 100% of the system voltage is 17 seconds. Maximum locked rotor current is 6 times that of full-load amperes (FLA). The MPD overload curve that we employ as a limit to calculate TCU, is shown in Figure 3. Please note that the location of this curve is between the hot and cold thermal limit curves supplied by the motor manufacturer. The time-current relation in this curve is per following equation:

$$T_{totrip}(sec) = \frac{87.4 \times 12}{I_{EQ}^2 - 1} \qquad (32)$$

- The Running and Stopped Motor Cooling Constants are respectively 20 and 40 minutes. Motor Service Factor = 1.15.
- Current Unbalance Factor: 6

Sequence 1: Combined operation (Figure 5)

State A. Initially the motor is at ambient temperature. TCU = 0%. The motor is ready to start.

Section AB. The motor is successfully started at 100% voltage. Acceleration time = 17.1 seconds, TCU accumulated during start is 46.7% (details are in Table 2)

Section BC. The motor runs for 45 minutes at a steady load of 80% with 10% current unbalance. TCU by the end of the period, exponentially decays to level of 19.5 %. TCU is calculated per equation 25.

Section CD. The Motor runs at 125% balanced overload for 15 minutes. TCU increments to the level of 67.7%.

Section DE. The Motor runs at 125% overload with 10% current unbalance until the thermal capacity reaches 100% and the relay trips the motor offline in 8.5 minutes. It is not well illustrated on the graph, but the addition of current unbalance at the running overload state decreases the trip time by 1.5 minutes or 15% (the calculated balanced overload trip time for the section DE is 10 minutes).

Section EF. The motor is at standstill and cools down to ambient temperature for 150 minutes. TCU decays to approximately 0 level. The rate of cooling is 2 times slower than of the running motor.
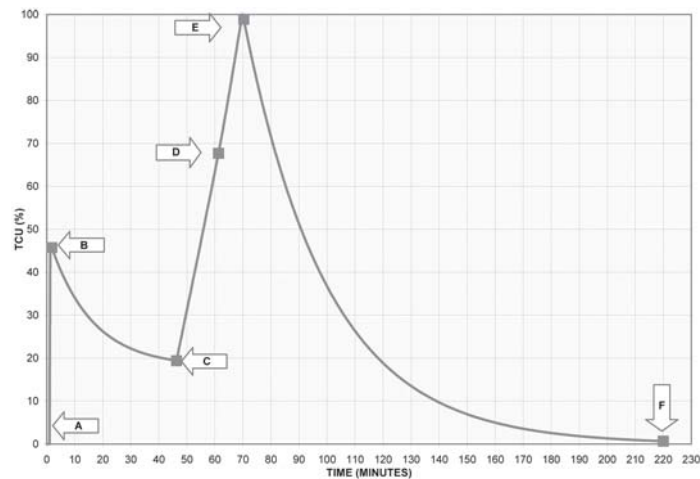

Fig 5.
Thermal capacity used during motor operation.

Sequence 2: Motor stall

The motor can be seriously damaged if a rotor stall occurs during the start attempt. Stall can occur due to a mechanical breakage or a human mistake. The stalled motor draws current equal to locked rotor amps. Locked rotor time (LRT) values provided by the motor manufacturer specify the thermal limit for the motor at ambient and rated conditions. Typically LRT is specified for the motor starts performed at 80% and 100% of the system voltages.
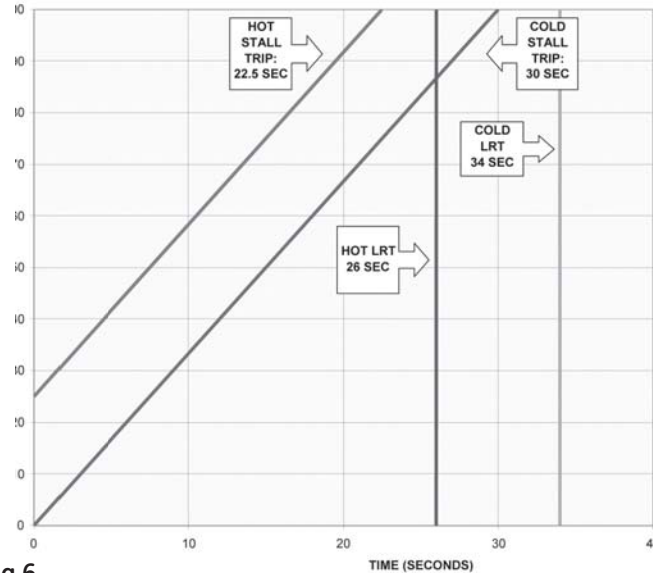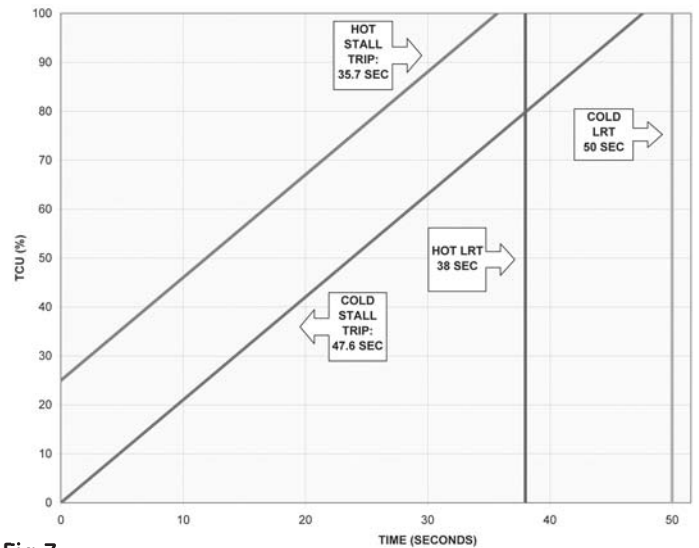

Fig 6.
Stall Trip. 100% Voltage

Fig 7.
Stall Trip. 80% Voltage

Figures 6 and 7 demonstrate how the thermal model provides an adequate protection where the motor is taken offline before the thermal limit is reached. This situation has been evaluated for hot and cold motor conditions at both 100% and 80% of the system voltages applied to the motor.

Sequence 3: Running overload

Three different scenarios are considered:

- The motor is overloaded immediately after a cold start.
- An overload is applied to the motor that was started, and, prior to overload, run unloaded for 2 hours.
- An overload is applied to the motor that was started and, prior to overload, run at full load for 2 hours.

The overload that was applied in all three cases was 125% of motor full-load amps.The motor thermal limit time values allow for applying a 125% overload to the cold and hot motor for 50 and 29 minutes respectively (data can be found in

Figure 3). The first case is characterized by severe heat generation in the rotor bars during the startup. Immediately following, the motor startup, the overload heats up the stator windings preventing heat transfer to the environment. This situation presents a serious thermal impact and the motor is taken offline faster in comparison to the other two cases. Trip time in this case is 16.3 minutes.

The second scenario presents an overload of the motor at ambient temperature. Initial TCU is 0%. According to the thermal model algorithm computations, the trip will be implemented 31 minutes after the overload is applied; which is lower than the cold motor limit (50 min). In a real application, the temperature of the unloaded running motor is typically higher than the ambient temperature, because of the associated motor losses. This fact explains why the significant margin between the cold overload trip time (31 min) and the cold thermal limit (50 min) is required.

The third scenario shows the hot overload (i.e. the motor is assumed to be at the rated temperature). The initial TCU in this case, the moment before the overload is applied, is 25%, so the tripping time is proportionally lower, compared to the cold overload. Tripping time in this case is 23 minutes, which is lower than the hot thermal limit (29 minutes).

Sequence 4: Consecutive starting

Per NEMA MG1 standard (11) medium and large induction motors are required to withstand thermally:

- 2 consecutive starts, coasting to rest between starts, with the motor initially at ambient temperature (cold starts)

- One start with the motor initially at rated load operating temperature (hot start)

An illustration of the thermal model response to consecutive starting is shown on Figure 8.

As you can see, the thermal model provides the start sequence required by NEMA.

An important enhancement to the thermal algorithm is the Start Inhibit function, which is employed to prevent excessive motor starting in cases where there is not enough thermal capacity available to perform a successful start. Modern intelligent
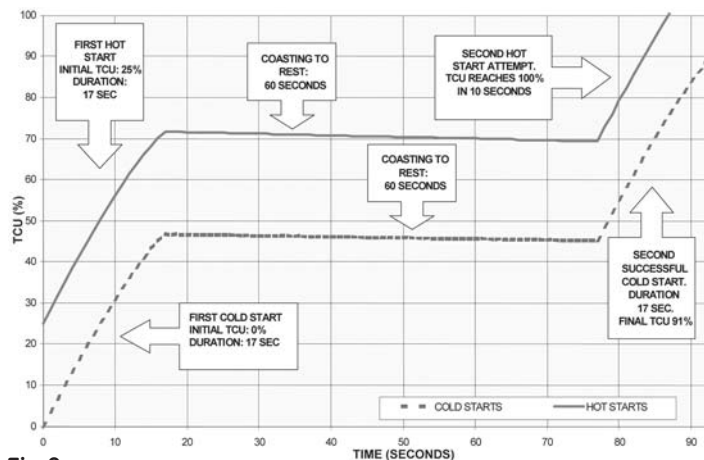
Fig 8.
Hot and Cold Consecutive Starts

protection devices are capable to learn and store, in the non-volatile memory, TC value utilized by motor during successful start and use this value in the start inhibit algorithm.

Sequence 5: Cyclic load

According to considerations discussed in a previous section of this paper, the main criterion for a thermal model's adequate response to cyclic load is the matching of the implied heating time-constant to the explicit running cooling time-constant (see equation 24). Let us review a balanced cyclic load (i.e. the effective heating) (equation 16) of 1.

After the cold start, the motor varies the load every 30 seconds at between 20% and 160% of the full-load current. Per equation 24, the running cooling constant is calculated as follows

$$\tau_{cool} = \frac{87.4 \times CM}{60} = \frac{87.4 \times 12}{60} = 17.5 (\text{min}) \tag{33}$$

In order to provide a more accurate thermal model response to cyclic load conditions, the cooling time-constant should be adjusted to the calculated value. At the same time this change (from 20 to 17.5 minutes) would cause no significant impact to the other motor operating sequences.

Figure 9 demonstrates the importance of cooling constant value in the thermal model response to cyclic load conditions.

Three cases are shown for a cycling load with an approximate per unit effective heating value of one. In the first case, the cooling time-constant is set long, resulting in over-protection and premature thermal model triggering. In the second case, the cooling time-constant is set to match the implied time-constant of the curve multiplier, and the thermal model adequately responds. In the third case, the cooling time constant is set short, resulting in under-protection and possible motor overheating.
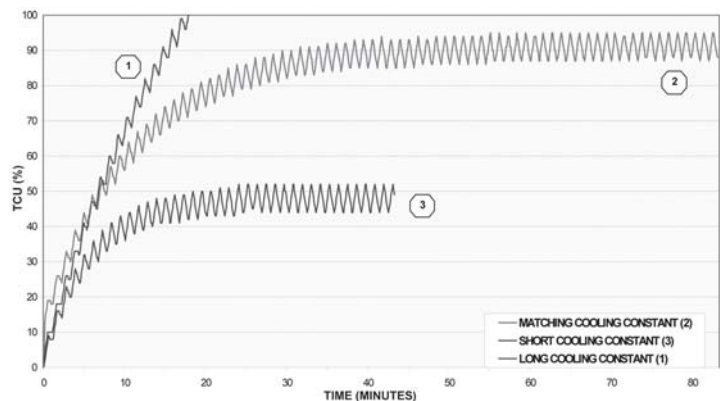
Fig 9.
Thermal model response to cyclic load

Sequence 6: Starting of high inertia loads

The thermal model algorithm has an additional enhancement that allows the coordination of protection with high-inertia long starts, while acceleration time is greater than the safe motor stall time. The voltage-dependant dynamic thermal limit curve is employed to account for varying thermal limits corresponding to the acceleration current levels at the different terminal motor voltages.

Figure 10 shows an example of a 100% voltage high inertia start

lasting 17 seconds (curve 1), and a locked rotor time limit of 8 seconds (curve 4). Actually curve 4 implies the line of the same I²T. In many short motor start applications it is reasonable to conservatively approximate that the thermal limit remains the same during motor acceleration. In the short start applications an error introduced by this assumption doesn't prevent the motor from successfully starting. The thermal limit curve is thus constructed from sections 2, 3 and 4. If the same approach is applied to the case shown on Figure 10, it will result in the TCU reaching 100% in the middle of the acceleration (Figure 11, curve 1).

As we mentioned in previous sections of this paper, as the thermal limit is a function of motor speed during acceleration, the acceleration thermal limit (curve 5) shows up differently from the locked rotor limit. Each point on curve 5 corresponds to current value which, in turn, corresponds to motor rotation speed during startup. Based on this, we can indirectly find the reference between motor speed and thermal limit, and construct an updated motor thermal limit curve which will include sections 2 and 5 shown on Figure 10.

The new curve helps achieve a successful motor start (Figure 11, curve 2) despite the fact that locked rotor safe time is shorter than acceleration period. The protection method described above is relevant for an ideal situation with a constant terminal voltage of 100%.

In reality the system voltage can deviate from 100% because of the voltage drop during motor startup. The locked rotor current (LRC) is almost directly proportional to the voltage applied to the motor terminals during acceleration, this fact must be taken into consideration when the acceleration portion of the thermal limit is used in the thermal model algorithm.
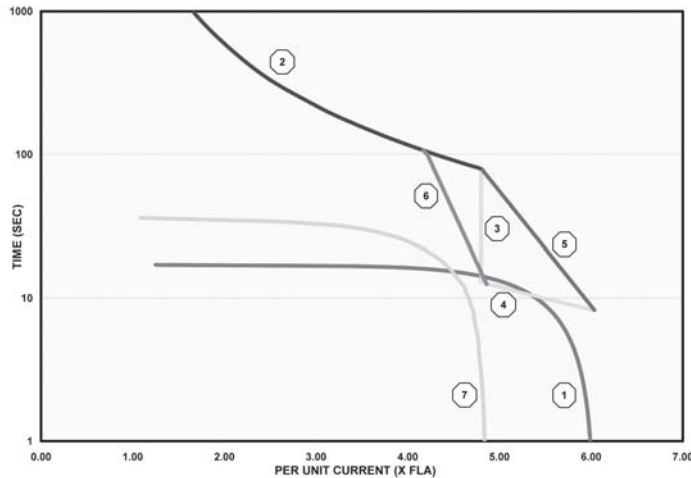

Fig 10.
Voltage Dependent Thermal Limit Curves

For example, for a 100% voltage start (Figure 10, curve 1) the locked rotor thermal limit is calculated based on a LRC of 6 times full load current (FLC) and 8 seconds of the allowed locked rotor safe time, and I²T is equal to 288. After 14 seconds the motor accelerates to approximately 80% of the rated speed and the current drops to the level of 4.8 times that of FLC.

The allowed time to withstand 4.8 FLA for this stage of acceleration is 40 seconds; I²T=922. Now let us consider the

same application reduced to 80% voltage start (Figure 10, curve 7). LRC at 80% is 4.8 times of FLC. From the 100% voltage case we know that the locked rotor condition is referenced to the thermal limit of 288, and the allowed locked rotor safe time for an 80% voltage start yields 12.5 seconds, but according to the acceleration thermal limit curve (Figure 10, section 5) the thermal limit time corresponding to 4.8FLC is 40 seconds which is much higher than the allowed value. This means that if the
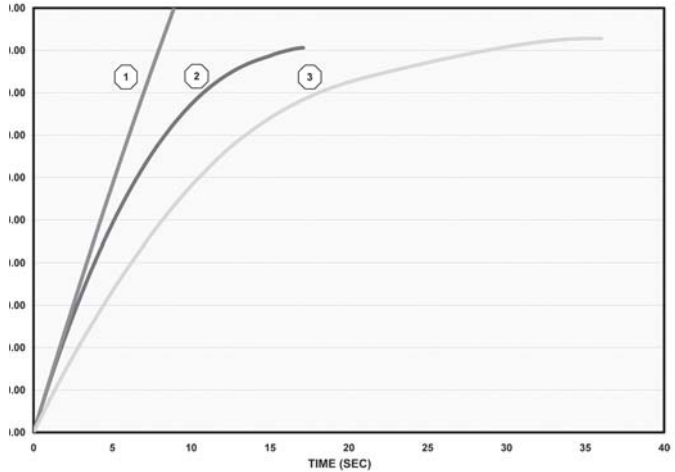

Fig 11.
Thermal Model Response to High Inertia Load Starts

motor stalls under the reduced voltage conditions it becomes underprotected and appears to be in real danger of burning.

To handle this situation the thermal model is equipped with a mechanism capable of dynamically responding to voltage variations during motor startup. Line 6 on Figure 10, shows the new position of the acceleration curve 4, shifted in response to the voltage reduction to 80%. The successful start under these operational conditions is shown on Figure 11, curve 3.

This technique provides adequate thermal protection in cases of high-inertia load application. In some cases where the thermal limit difference between locked rotor and acceleration conditions is not clearly identified, this element should be supported with a zero speed sensor.

6. Application Description

This case study examines the Induced Draft (ID) fan application on the A. B. Brown Unit 2 Selective Ccatalytic Reduction (SCR) Project, located in Evansville, Indiana. Unit 2 is owned by Vectren Corporation, and the role of Black & Veatch (B&V) on this project was to construct an SCR facility in this plant.

The SCR Project Scope of Work included modifying both ID fans for catalyst draft losses. The motors were powered from 13.8 kV switchgear.

Motor ratings and data

Motor Parameter	Value
Motor Horse Power	5500 HP
Rated Voltage	13200 V
Phases	3
Motor Full Load	893 RPM
Service Factor	1.15
Frequency	60 Hz
Rated Full Load Current	226 A
Rated Locked Rotor Current	1205 A
Insulation Class	F
Ambient Temperature	43° C
Temperature Rise @ SF=1.0	77° C
Temperature Rise @ SF=1.15	87° C

Table 3.
Basic Motor Data

Table 3 presents the motor information pertaining to the ID fan motors.

Motor starting and thermal characteristics

The motor manufacturer provided the thermal limit curve under locked rotor, acceleration, and running overload conditions, as well as time-current curves during acceleration at rated voltage and at minimum specified starting voltage. Some of the important motor characteristics (from the manufacturer's data sheet and curves) are summarized in Table 4.

Motor Data		
Description	Voltage	Value
Acceleration time @ Rated Voltage in Seconds	100%	28.0
Acceleration time @ minimum Voltage in Seconds	80%	53.0
Cold Locked Rotor Safe Stall Time @ rated voltage and ambient temperature in seconds	100%	26.0
Cold Locked Rotor Safe Stall Time @ min voltage and ambient temperature in seconds	80%	47.0
Hot Locked Rotor Safe Stall Time @ rated voltage at service factor load operating temperature in seconds	100%	23.0
Hot Locked Rotor Safe Stall Time @ min voltage at service factor load operating temperature in seconds	80%	42.0
Maximum Starts Per Hour	N/A	2
Maximum Cold Consecutive Starts @ rated Voltage	100%	2
Maximum Cold Consecutive Starts @ min Voltage	80%	2
Maximum Hot Consecutive Starts @ rated Voltage	100%	1
Maximum Hot Consecutive Starts @ min Voltage	80%	1
Running Cooling Time Constant in minutes	N/A	9
Initial / Modified (during Startup) Stopped Cooling Time Constants in minutes	N/A	16 / 12

Table 4.
Motor Starting and Thermal Limit Characteristics

Protection philosophy

The ID fans on the A. B. Brown Project are fed from a 13.8 kV auxiliary electric system and are protected by a multifunction motor protection device (MPD). The fundamental philosophies used in setting the MPD are as follows:

- The relay provides thermal protection of the motor during abnormal starting or running conditions, preventing thermal damage to the motor (i.e., the MPD curve is placed below the motor thermal damage curves).

- The relay allows the motor to be started successfully without nuisance trips, in accordance with the number of starts and thermal/cooling characteristics recommended by the manufacturer

- The relay settings allow proper coordination with the respective tie and main circuit breakers on the 13.8 KV bus to which the motors are connected.

Typically the B&V specifications require the motor design to meet the following criterion:

"Motor safe stall time at minimum starting voltage shall not be less than motor acceleration time at minimum starting voltage, plus 2 seconds." The motor manufacturer could not meet this requirement for this high-inertia application and indicated that a speed switch would be provided in lieu of this requirement. The speed switch option was not used because the MPD provided a range of setting options for the overload feature. The MPD was originally set using the custom overload curve feature to match the motor characteristics, in addition to all the above listed protection criteria.

Problems during startup of ID fans

The problem that the commissioning team faced during startup was that the successive motor start-time delays determined by the MPD thermal model were inconsistent with what was allowed by the motor manufacturer. The motor data sheet allowed the following operational characteristics:

- Two successive cold starts or one hot start.

- Following this sequence a new start would be allowed after any of the following:

  - A cooling period of 40 minutes if the motor was running at service factor load and then stopped.

  - A cooling period of 10 minutes if the motor was running unloaded and then stopped.

  - A cooling period of 20 minutes if the motor was de-energized, coasted to rest, and left idle.

It was observed that the MPD was delaying restart by 40 to 43 minutes after every start attempt, regardless of whether it was a second cold restart or the first hot restart. This performance was unacceptable to the client who wanted reliable cold starting as well as a restart time consistent with that indicated by the motor manufacturer. Some of the motor parameters recorded in the MPD during the startup of one of the fans are as follows:

- Hottest RTD Values: 70° C.

- Learned Starting Current: 1.085 A.

- Average Motor Load: 60 percent of the rated current.

It was also noticed that the MPD thermal model was accumulating almost all the available thermal capacity even during the first cold successful start, thus preventing

the motor from performing a successive start. The MPD did not allow a restart for 40 to 43 minutes because of the start-inhibit feature that prevented further restarts when the available thermal capacity was not sufficient for a successful start. This performance was found to be inconsistent with the motor manufacturer's recommendations. B&V requested the involvement of the motor and relay manufacturers to resolve this apparent problem.

Solution to the problem

B&V closely coordinated with all the parties, and the following measures were put in place in sequence:

- The motor manufacturer provided the following recommendations regarding the thermal model settings of the MPD:

  – Use the voltage-dependent overload curve option available in the MPD, and set it with reference to the motor thermal damage curve.

  – To better model the motor during the 9 minutes of coast-down period, decrease the stopped cooling time-constant to 12 minutes.

  – Decrease the safety margin in the start-inhibit function to shorten the lockout time between starts. (The safety margin was changed from 25 to 5 percent.)

- Acting on these recommendations, the relay manufacturer, B&V, and the motor manufacturer collaboratively reviewed the motor protection coordination and relay set points. The following actions were taken:

  – The relay overload curve was changed to the voltage dependent overload curve, with the revised relay points on the hot thermal curve for the starting zone.

  - The stopped cooling time-constant was programmed as 12 minutes, reduced from 16 minutes.

  - Acceleration time was changed to 35 seconds because the motor was observed to start and accelerate satisfactorily within approximately 28 seconds.

  - The thermal capacity used margin set point was changed from 25 to 5 percent.

  - The jogging block function was left on, and the maximum number of starts was programmed to be 2; time between starts was programmed to 0.

  - The restart block was enabled and set to 10 minutes (600 seconds) to comply with the motor requirements of coasting to rest (9 minutes) after being de-energized, before the new start would be allowed.

  - The RTD bias of the thermal model was disabled because it was inappropriate for this application. It is important to mention here that B&V, as part of the control design, always programs an alarm in the relay for high temperature based on RTD inputs.

  - The thermal capacity alarm level setting was left at 85 percent to be readjusted later if required.

Did it work?

The synergistic efforts to problem solving between B&V, the relay manufacturer, and the motor manufacturers paid off. The implementation of voltage-dependent overload curves resolved the issue of unreliable motor starting, and the motor successive restart time delay was reduced to around 20 minutes to the satisfaction of the client. The fans have been successfully commissioned and are now running without problems at the A. B. Brown plant.

Lessons Learned from This Experience

The cited case study highlights the need for flexibility and collaboration between all parties and, above all, a customer-oriented approach to relay coordination studies for complex motor applications. The following are some of the salient lessons:

- The relay application engineer should obtain accurate information about the motor before designing the relay settings. In this respect, it is important that the motor's certified acceleration curves provided by the motor vendor match actual conditions. In addition, the proper cooling time-constants recommended by the motor manufacturer, must be programmed into the relay so that motor behavior may be simulated accurately.

- The motor manufacturer must be consulted and requested to concur on overload relay selection curves in applications where the motor starting curves and the thermal damage curves are very close to one other. The solution that was arrived at in the A. B. Brown case study, where a portion of the overload curve was set on the motor thermal curves, would not have been possible without the motor manufacturer's concurrence.

- All efforts must be made to achieve safe operation of the motor and adequate coordination with other devices and, at the same time, meet the operational expectations of the application.

7. Conclusions

The modern industrial marketplace has a strong demand for a simple, reliable, accurate, multifunctional MPD designed in accordance with industry standards. The major element of a MPD is the thermal model, which must create an accurate image of the motor thermal conditions at any stage of the protected machine's operation.

Theoretical considerations prove that a simplified thermal model based on an equivalent single time-constant model, and overload curves matching motor manufacturers standards for thermal limits, can provide adequate protection at a level of accuracy desirable for this type of application. It can be clearly demonstrated that if the implied thermal constant of the overload curve matches the explicit cooling constant of the running motor, the relay algorithm computes the correct thermal image of the motor during a cycling load.
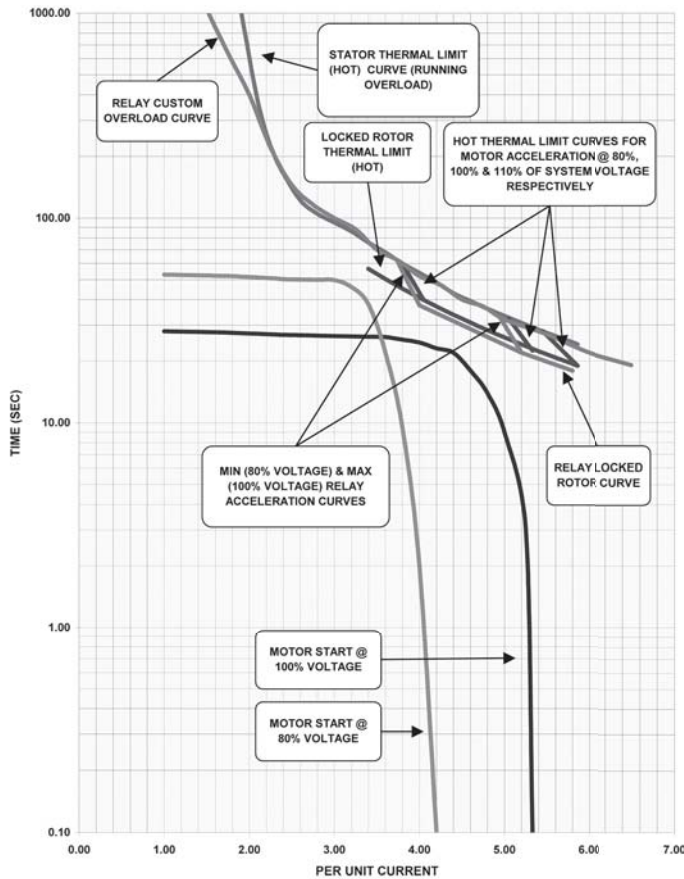
Fig 12.
Coordination of ID Fan Motor Thermal Limit Curves and MPD Thermal Protection Curves.

A detailed explanation of the thermal algorithm actually provides the tools required to calculate the thermal capacity for literally any application. In many cases, it is useful to evaluate thermal model behavior before motor energizing and compare the results with operation restrictions dictated by the motor manufacturer. Analysis of typical motor sequences based on real motor specification data shows how the thermal model algorithm implemented in an MPD can successfully handle excessive motor operation duty and avoid stator and rotor overheating as well as premature machine tripping because of thermal overestimation.

Thousands of motor protection systems employing the proposed thermal algorithm have been successfully installed in various motor applications. However, in a few instances, the setting of motor thermal protection is not as straightforward as it is in the majority of cases.

The A. B. Brown case study presents a unique situation where the close coordination between the parties involved (the end-user, the application engineer, the relay manufacturer and the motor manufacturer) allowed the refinement of application-related information so that proper thermal protection and coordination during commissioning could be provided.

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